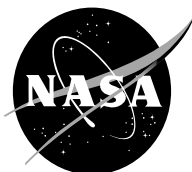


NASA Technical Memorandum 4538

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FLIGHT-DETERMINED ENGINE EXHAUST CHARACTERISTICS OF AN F404 ENGINE IN AN F-18 AIRPLANE

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Abstract

Personnel at the NASA Langley Research Center (NASA-Langley) and the NASA Dryden Flight Research Facility (NASA-Dryden) have recently completed a joint acoustic flight test program. Several types of aircraft with high nozzle pressure ratio engines were flown to satisfy a twofold objective. First, assessments were made of subsonic climb-to-cruise noise from flights conducted at varying altitudes in a Mach 0.30 to 0.90 range. Second, using data from flights conducted at constant altitude in a Mach 0.30 to 0.95 range, engineers obtained a high-quality noise database. This database was desired to validate the Aircraft Noise Prediction Program and other system noise prediction codes. NASA-Dryden personnel analyzed the engine data from several aircraft that were flown in the test program to determine the exhaust characteristics. The analysis of the exhaust characteristics from the F-18 aircraft will be reported in this paper. This paper presents an overview of the flight test planning, instrumentation, test procedures, data analysis, engine modeling codes, and results.

Nomenclature

A8	exhaust nozzle physical area at the throat, in ²
AE8	exhaust nozzle effective throat area, in ²
AE9	exhaust nozzle effective area at the exit plane, in ²
ANOPP	Aircraft Noise Prediction Program

<i>FG</i>	gross thrust, lb
HSCT	high-speed civil transport
M_9	nozzle exit Mach number
M_{jet}	fully expanded jet Mach number
M_∞	free-stream Mach number
NPR	nozzle pressure ratio, P_8/P_{amb}
P_8	total pressure at the exhaust nozzle throat, psia
PLA	power lever angle, deg
P_{amb}	ambient pressure, psia
P_{s9}	static pressure at the exit plane, psia
T_8	total temperature at the exhaust nozzle throat, °R
V_9	nozzle exit velocity, ft/sec
V_{jet}	fully expanded jet velocity, ft/sec
V_∞	free-stream velocity, ft/sec
W8	mass flow rate at the exhaust nozzle throat, lb/sec

Introduction

Environmental issues are a significant concern confronting the designers of future high-speed civil transport (HSCT) airplanes. It has been determined that a substantial market will exist for HSCT aircraft if designers meet key environmental issues, one of which is noise. The HSCT aircraft must keep takeoff, climb-to-cruise, and landing noise levels within the Federal Aviation Regulation, part 36, Stage III community noise standards.¹

The HSCT design concept will likely have supersonic cruise speeds between Mach 2.00 and 2.50. Engines capable of efficient flights at speeds above Mach 2.00 will likely have the thermodynamic cycle of a turbojet or a very-low-bypass turbofan.² These engines have high

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nozzle pressure ratios (NPRs) and jet velocities, which raises concern not only for takeoff and landing noise, but also for climb-to-cruise noise, extending from the airport for a distance of up to 50 miles.

To determine the predicted noise of HSCT aircraft, acoustic codes such as ANOPP (Aircraft Noise Prediction Program)³ are used. These codes were developed using data acquired from engines with NPRs and flight speeds lower than those planned for HSCT aircraft.

To better understand the acoustic characteristics of engines representative of HSCT designs and to enhance current noise prediction codes, personnel at NASA Langley Research Center (NASA-Langley) and NASA Dryden Flight Research Facility (NASA-Dryden) have conducted joint flyover acoustic testing to acquire data.⁴ The test objective was first, to assess subsonic climb-to-cruise noise using aircraft with high NPR engines and second, to obtain an improved noise database to validate ANOPP and other system noise prediction codes. The NASA-Dryden personnel conducted the flyover tests and determined the engine exhaust characteristics. The NASA-Langley personnel made the acoustic measurements, performed the correlations between the engine exhaust characteristics and acoustic data, and updated the ANOPP code.

The flight study consisted of a series of flights over microphone arrays using several types of aircraft. In the subsonic climb portion of the study, the flight matrix consisted of flyovers at intermediate power at altitudes from 3800 to 32,000 ft and Mach numbers from 0.30 to 0.95. For the ANOPP evaluation flyovers, the test points were conducted at a constant altitude and Mach number. A ground static acoustic test was also conducted to establish acoustic levels with no forward velocity.

For all of the tests, the measured engine data were collected and later analyzed by an F404-GE-400 in-flight thrust code. The code predicted the engine exhaust characteristics of exhaust velocity and Mach number, which cannot be directly obtained from the measured engine data.

This paper describes the F-18 airplane, the F404 engine, the flight test program, and the methods used to calculate the engine exhaust properties. In addition, the paper presents the exhaust velocity and Mach number data for the climb-to-cruise, ANOPP validation, and ground tests.

Aircraft Description

F-18 Aircraft

Figure 1 shows an F-18 aircraft (McDonnell Douglas Corp., St. Louis, Missouri and Northrop Corp., Newbury

Park, California) during one of the test runs. This supersonic, high-performance fighter has excellent transonic maneuverability and is powered by two F404-GE-400 (General Electric Co., Lynn, Massachusetts) afterburning, turbofan engines.⁵ Both engines are mounted close together in the aft fuselage. The standard F-18 maintenance data recorder was used onboard the aircraft to record a limited number of airplane and engine parameters.

Engine Description

The F404-GE-400 is a two-spool, low-bypass, axial-flow turbofan with afterburner. The engine consists of a three-stage fan driven by a single-stage, low-pressure turbine and a seven-stage, high-pressure compressor driven by a single-stage, high-pressure turbine. Variable geometry is incorporated into the fan and high-pressure compressor and the nozzle is a convergent-divergent nozzle.⁶ It is equipped with an engine control unit (ECU) where idle power is 35° power lever angle (PLA) and intermediate (maximum nonafterburning) power is 102° PLA. It produces NPRs similar to those expected of an HSCT engine application.

Test Procedures

Ground Track

The flight tests were flown over the Rogers Dry Lake which is adjacent to NASA-Dryden. Located at an elevation of 2300 ft, this dry lakebed provides a flat, interference-free area for acoustic testing. Figure 2 shows the approximate location of the microphone array placed along the “fly-by” line on the northeast side of the lakebed. This area was ideal for tracking because of its close proximity to the NASA-Dryden radar site. Using the ground track and distance displayed in the control room, the pilots were guided down the ground track and over the acoustic array. Flight conditions such as altitude or Mach number needed to be kept as constant as possible to get good quantitative runs. There were 95 recorded F-18 flyovers.

Flight Procedures

The flight tests were conducted in two segments: subsonic climb to cruise and ANOPP validation. A single-exhaust jet was desired so the acoustics tests would have one distinct noise source. For the twin-engine F-18 aircraft both engines were used to set up the initial conditions before the beginning of a maneuver. On call from the control room, the pilot stabilized the speed and altitude of the aircraft. The left engine was throttled back to idle while the right test engine was operated at intermediate power. This procedure simulated the effect of a single engine. For the ANOPP validation segment the test engine was

operated at the power required to maintain level flight. The F-18 maintenance recorder was activated by the pilot and operated for 35 sec to record aircraft and engine data during the run. Table 1 shows the flight matrix for the climb-to-cruise and ANOPP validation segments of the flight test.

Climb-to-Cruise Test Matrix

The flight matrix for the climb-to-cruise segment consisted of level flight accelerations at various Mach numbers and altitude to simulate points along a expected HSCT climb profile. Altitudes varied from 3800 to 32,500 ft and speeds ranged from Mach 0.30 to 0.90. The aircraft flew with the right test engine at the intermediate power setting to maximize NPR.

ANOPP Validation Test Matrix

The ANOPP evaluation segment was flown at a constant altitude of 3800 ft (1500 ft above the ground) with speeds ranging from Mach 0.30 to 0.95. Power settings on the test engine varied depending on what was required to maintain constant flight speed or Mach number and altitude.

Ground Test

In addition to the flight testing, static ground tests were conducted with the aircraft tied down on the thrust stand pad at the US Air Force Flight Test Center at Edwards, California. The test matrix consisted of PLAs from idle to intermediate power at 0.1 increments in engine pressure ratio. The F-18 onboard recorder maintenance tape was run for 35 sec at each power setting to record the engine data. Temperature, wind speed, and wind direction were also recorded. The tests were conducted with the wind speeds below 5 kts.

Engine Exhaust Characteristics

Jet-mixing and shock cell noise are the two primary sources of noise for takeoffs and subsonic climbs.⁷ These noise sources are primarily affected by the aircraft velocity, the exhaust exit Mach number and velocity, and the NPR. For acoustic analysis, engine exhaust characteristics are often defined at the nozzle exit and an assumed fully expanded jet. Jet-mixing noise is a function of the difference between the fully expanded jet velocity (V_{jet}) and the free-stream velocity (V_∞). Shock cell noise is a function of the difference between the fully expanded jet Mach number (M_{jet}) and the nozzle exit Mach number (M_9). As you approach the point where $M_9 = M_{jet}$ and $V_\infty = V_{jet}$, the shock cell noise and jet-mixing noise are diminished. Nozzle exit velocity (V_9) and M_9 are based on the aero-

thermodynamic characteristics of the flow at the nozzle exit plane (Fig. 3).

F404 In-Flight Thrust Code

Data obtained from the engine during the flight and ground tests included compressor speed, compressor discharge pressure, fan speed, fuel flow, inlet temperature, turbine discharge temperatures, turbine discharge pressure, and nozzle area ratio. Measured engine data obtained from the flight tests do not directly give the values of M_9 , V_9 , M_{jet} , and V_{jet} needed for acoustic analysis with the ANOPP prediction code. As a result, the measured engine data must be input into the engine performance codes to obtain the desired engine exhaust characteristics.

The F404-GE-400 in-flight-thrust performance code⁸ was developed by the General Electric Co. for the US Navy. This code models the engine as a gas generator and uses the measured engine parameters as input. The performance code calculates the following parameters throughout the flight envelope: gross thrust (FG), V_9 , V_{jet} , M_9 , M_{jet} , NPR, exhaust nozzle effective exit area to effective throat area ratio ($AE9/AE8$), exhaust nozzle static exit pressure to ambient pressure ratio ($Ps9/Pamb$), exhaust nozzle throat total temperature ($T8$), and exhaust nozzle throat mass flow rate ($W8$). The exhaust nozzle exit mass flow rate ($W9$) and total temperature ($T9$) are assumed to be equal to $W8$ and $T8$, respectively.

The following assumptions are used in the in-flight thrust code. Steady one-dimensional isentropic flow is assumed between the throat and the nozzle exit. Based on the resulting nozzle static exit pressure ($Ps9$), the flow will be overexpanded ($Ps9 < Pamb$), fully expanded ($Ps9 = Pamb$), or underexpanded ($Ps9 > Pamb$). M_{jet} is based on the point where the flow is fully expanded ($Ps9 = Pamb$) and it is a function of NPR. M_9 is a function of nozzle area ratio. Once M_9 and M_{jet} are determined, V_9 and V_{jet} are then calculated. V_9 represents the actual exhaust exit velocity while V_{jet} represents the ideal fully expanded jet exhaust velocity. If the actual exhaust velocity were fully expanded, V_9 would match V_{jet} .

Results and Discussion

Climb-to-Cruise Test Results

Figure 4 shows the effect of Mach number on F404 engine exhaust characteristics for climb-to-cruise tests at intermediate power. Figure 4(a) shows the relationship between V_{jet} and V_9 and the free-stream Mach number (M_∞). Each point on the curve represents a different altitude in the climb-to-cruise matrix. At the beginning of the climb profile when the altitude is approximately 3800 ft and $M_\infty \approx 0.30$, the nozzle is overexpanded ($V_9 > V_{jet}$).

The point where the data crosses, $M_\infty \approx 0.85$ and $V_{jet} = V_9$, indicates that the nozzle is fully expanded. When the climb profile reaches an altitude of approximately 32,300 ft and $M_\infty \approx 0.90$, the nozzle is underexpanded ($V_9 < V_{jet}$). Overall, V_9 varies from $V_9 \approx 2750$ ft/sec up to a maximum of $V_9 \approx 2800$ ft/sec, and then drops to a value of $V_9 \approx 2750$ ft/sec, while V_{jet} varies from 2300 to 2900 ft/sec.

Figure 4(b) shows M_{jet} and M_9 as a function of M_∞ . M_{jet} and M_9 follow the same trends with Mach number and altitudes as V_{jet} and V_9 . The values of M_9 vary between 1.69 up to a maximum of $M_9 \approx 1.80$, and then drop to $M_9 \approx 1.70$. The values of M_{jet} vary between $M_{jet} \approx 1.35$ up to a maximum of $M_{jet} \approx 1.76$. Above $M_\infty \approx 0.85$, the difference between the two values is significantly reduced. Table 2 lists other parameters of interest for the climb-to-cruise test. The maximum nozzle pressure ratio was 5.24.

ANOPP Validation Test Results

Figure 5 shows the effect of Mach number on F404 engine exhaust characteristics for ANOPP validation tests at a level altitude of 3800 ft. Figure 5(a) shows the exhaust velocities V_9 and V_{jet} with respect to M_∞ . The power setting (PLA) of the test engine was set at the level (shown in parentheses) necessary to maintain constant Mach number in level flight while the other engine remained at idle. The power settings varied from partial power (75°) at the lower speeds, to intermediate power (102°) at the higher speeds. As in Fig. 4, both V_9 and V_{jet} were plotted as a function of M_∞ ; however, no crossover occurred because at this low altitude the nozzle is overexpanded for this M_∞ range. The values of V_9 varied from $V_9 \approx 2550$ ft/sec up to a maximum of $V_9 \approx 2900$ ft/sec, while V_{jet} varied between $V_{jet} \approx 1900$ to 2650 ft/sec.

Figure 5(b) shows a plot of exhaust Mach numbers M_9 and M_{jet} with respect to M_∞ . This set of data also shows a steady trend of increased M_9 and M_{jet} without any crossover of the data. The two curves do converge toward each other indicating that a fully expanded nozzle condition may occur at a higher M_∞ . The values of M_9 were $M_9 \approx 1.70$ to 1.80 while M_{jet} varied from $M_{jet} \approx 1.15$ to 1.60. Table 3 shows additional parameters of interest for the ANOPP validation test.

Ground Test Results

For the ground static tests the effect of PLA on F404 engine exhaust characteristics is shown in Fig. 6. Figure 6(a) shows V_9 and V_{jet} plotted against PLA for the ground tests. The values of V_9 varied from $V_9 \approx 2500$ to 2800 ft/sec with increasing PLA. V_{jet} varied from $V_{jet} \approx 1800$ to 2200 ft/sec. Figure 6(b) shows the relationship of

PLA to exhaust Mach numbers M_9 and M_{jet} . The values of M_9 varied between $M_9 \approx 1.71$ to 1.74 and M_{jet} varied between $M_{jet} \approx 1.08$ to 1.30. The data for the exhaust Mach numbers show a trend similar to the exhaust velocities in Fig. 6(a). Additional data for the ground tests are listed in Table 4.

The data in the tables and figures are typical points taken from the many runs conducted in the study. They matched the desired altitudes and Mach numbers shown in the flight matrix in Table 1. The data were selected from test points with stable engine conditions. These points were not averaged. The overall results show that the engine exhaust characteristics of interest for the acoustic test vary with M_∞ , altitude, and PLA. Tables 2, 3, and 4 show that from the climb-to-cruise, ANOPP validation, and ground tests the peak V_9 values were approximately 2800 to 2900 ft/sec.

Concluding Remarks

A series of acoustic tests were conducted, first, to determine climb-to-cruise noise of aircraft with high nozzle pressure ratios and second, to validate the Aircraft Noise Prediction Program (ANOPP). An F-18 airplane, with the F404-GE-400 engine installed, was flown over a range of flight speeds and altitudes. From these tests, the engine data were analyzed to determine their exhaust characteristics. The flight tests produced a large engine exhaust characteristics database that was correlated with acoustic data and used to upgrade the ANOPP code. This new database will aid in the design of future high-speed civil transport (HSCT) aircraft.

In summary, the climb-to-cruise test conditions at intermediate power produced engine exhaust conditions that varied from overexpanded to underexpanded. The nozzle exit velocities ranged from approximately 2750 ft/sec up to a maximum of approximately 2800 ft/sec, and then dropped to a value of approximately 2750 ft/sec. The nozzle exit Mach numbers ranged between Mach 1.69 up to a maximum of Mach 1.81 and then dropped to a value of Mach 1.70. The maximum nozzle pressure ratio was 5.24. For the ANOPP validation test points, the exhaust conditions were overexpanded and nozzle exit velocity ranged from approximately 2550 to 2900 ft/sec. Nozzle exit Mach numbers ranged from approximately Mach 1.70 to Mach 1.81. For the ground test conditions, nozzle exit velocity varied from 2500 to 2800 ft/sec. Nozzle exit Mach number remained fairly constant at Mach 1.70 over the range of power levels tested. For the three tests: climb-to-cruise, ANOPP, and the ground run, at intermediate power, maximum nozzle exit velocities were approximately 2800 to 2900 ft/sec and nozzle exit Mach number was approximately Mach 1.70.

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Table 1. Flight matrix for climb-to-cruise points and ANOPP validation.

Test matrix				
Climb to cruise			ANOPP	
Altitude, ft (mean sea level)	Free-stream Mach number	Altitude, ft (mean sea level)	Free-stream Mach number	
3,800	0.30	3800	0.30	0.30
7,300	0.60	3800	0.40	0.40
12,300	0.65	3800	0.65	0.65
22,300	0.75	3800	0.75	0.75
32,300	0.90	3800	0.95	0.95

Table 2. Primary data associated with climb-to-cruise test points.

Climb-to-cruise points												
Throttle, deg	M_∞	Altitude, ft	NPR	T^8 , °R	W^8 , lb/sec	A^8 , in ²	$AE9/AE8$	$Ps9/Pamb$	FG , lb	M_9	$V_{g'}$, ft/sec	$V_{jet'}$, ft/sec
102	0.32	3,850	2.930	1687.0	127.6	274.6	1.430	0.539	9125.0	1.69	2744.00	2305.0
102	0.61	7,292	3.090	1683.6	132.7	298.3	1.490	0.531	9703.2	1.81	2871.51	2388.3
102	0.68	12,324	3.375	1689.6	116.6	293.4	1.470	0.588	8810.1	1.80	2861.18	2465.6
102	0.77	22,331	4.420	1687.2	89.2	261.5	1.390	0.868	7380.7	1.73	2779.82	2679.2
102	0.89	32,307	5.240	1682.9	66.4	251.2	1.360	1.071	5726.0	1.70	2749.14	2796.0

Table 3. Primary data associated with ANOPP validation test points.

ANOPP points													
Throttle, deg	M_{∞}	Altitude, ft	NPR	T8, °R	W8, lb/sec	A8, in ²	AE9/AE8	P _{s9} / P _{amb}	FG, lb	M ₉	V ₉ , ft/sec	M _{jet}	V _{jet} , ft/sec
75	0.34	3745	2.244	1423.5	92.82	249.2	1.380	0.440	5304.8	1.722	2543.98	1.151	1887.81
80	0.61	3800	2.782	1542.9	107.05	245.3	1.350	0.778	7119.2	1.692	2621.38	1.317	2183.69
100	0.80	3795	3.658	1718.7	163.51	303.3	1.488	0.628	12672.6	1.811	2896.83	1.515	2555.67
102	0.92	3845	4.136	1713.0	177.54	297.2	1.459	0.737	14289.3	1.787	2867.34	1.559	2649.41

Table 4. Primary data associated with ground-test points.
Table 4. Primary data associated with ground-test points.

Ground-test points													
Throttle, deg	M_{∞}	Altitude, ft	NPR	T_8 , °R	W8, lb/sec	A8, in ²	AE9/AE8	P_{s9}/P_{amb}	FG , lb	M_9	V_9 , ft/sec	M_{jet}	$V_{jet'}$ ft/sec
80	---	2350	2.055	1437.3	91.3	249	1.24	0.413	4978.5	1.71	2542.60	1.08	1800.7
87	---	2350	2.330	1527.8	100.7	249	1.28	0.465	6121.9	1.71	2629.35	1.18	1998.0
92	---	2350	2.610	1622.1	110.1	249	1.28	0.520	7326.3	1.70	2701.63	1.27	2176.3
102	---	2350	2.720	1671.9	120.6	264	1.32	0.520	8717.7	1.74	2784.81	1.30	2252.6

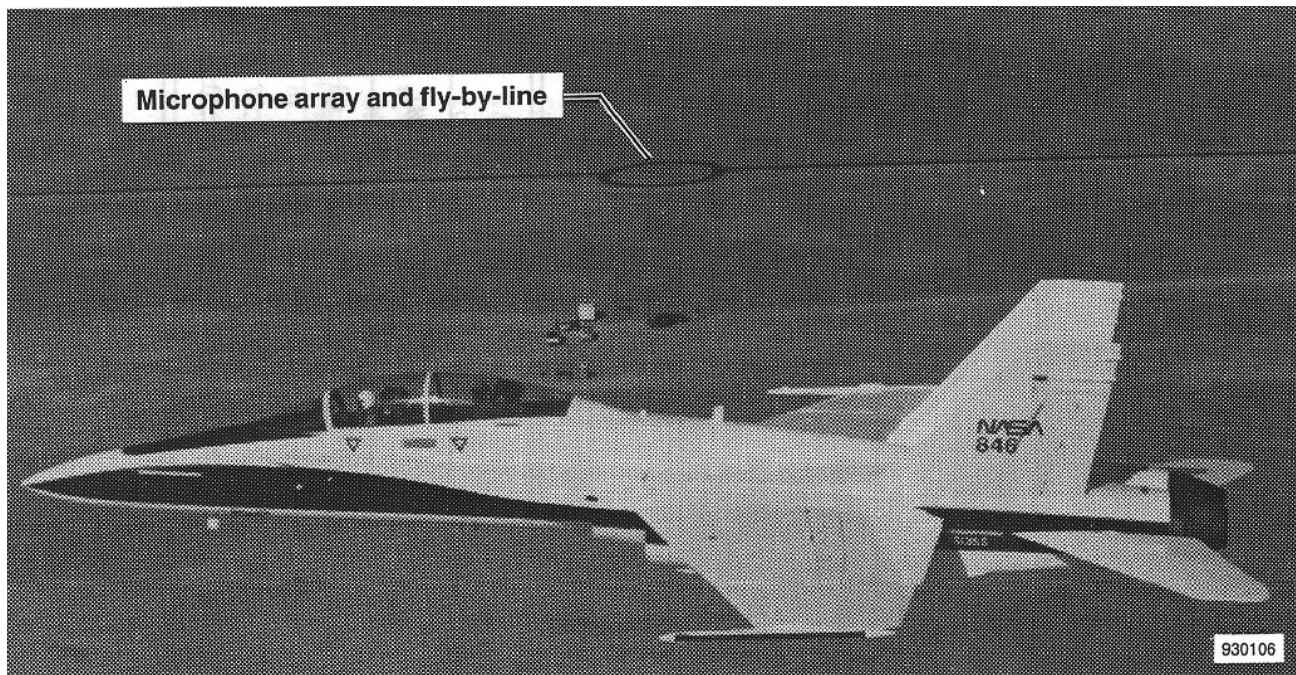


Fig. 1 F-18 aircraft powered by two F404-GE-400 engines.

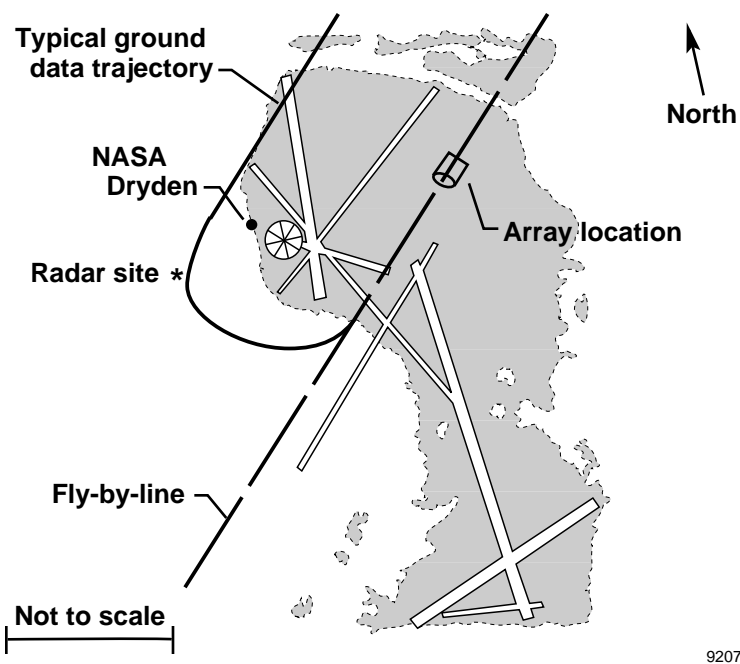


Fig. 2 Ground-tracking and array layout at Rogers Dry Lake, Edwards, California.

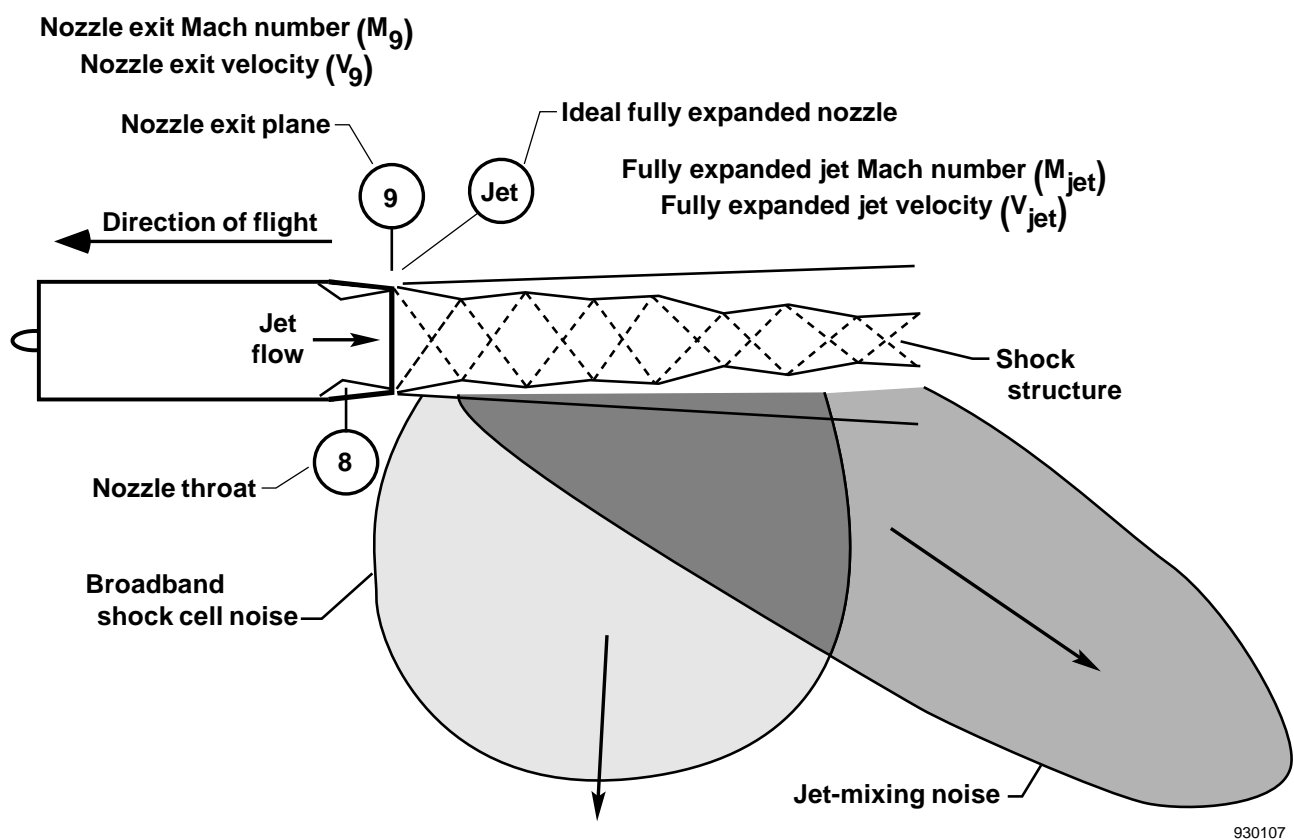
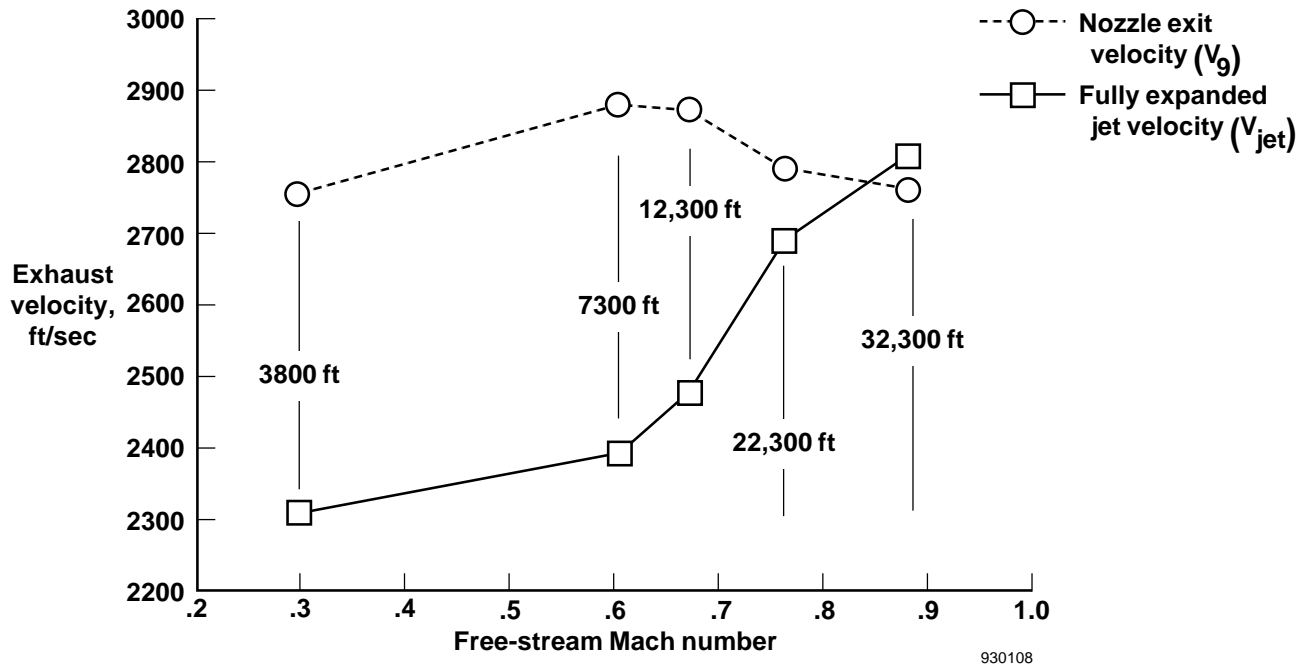
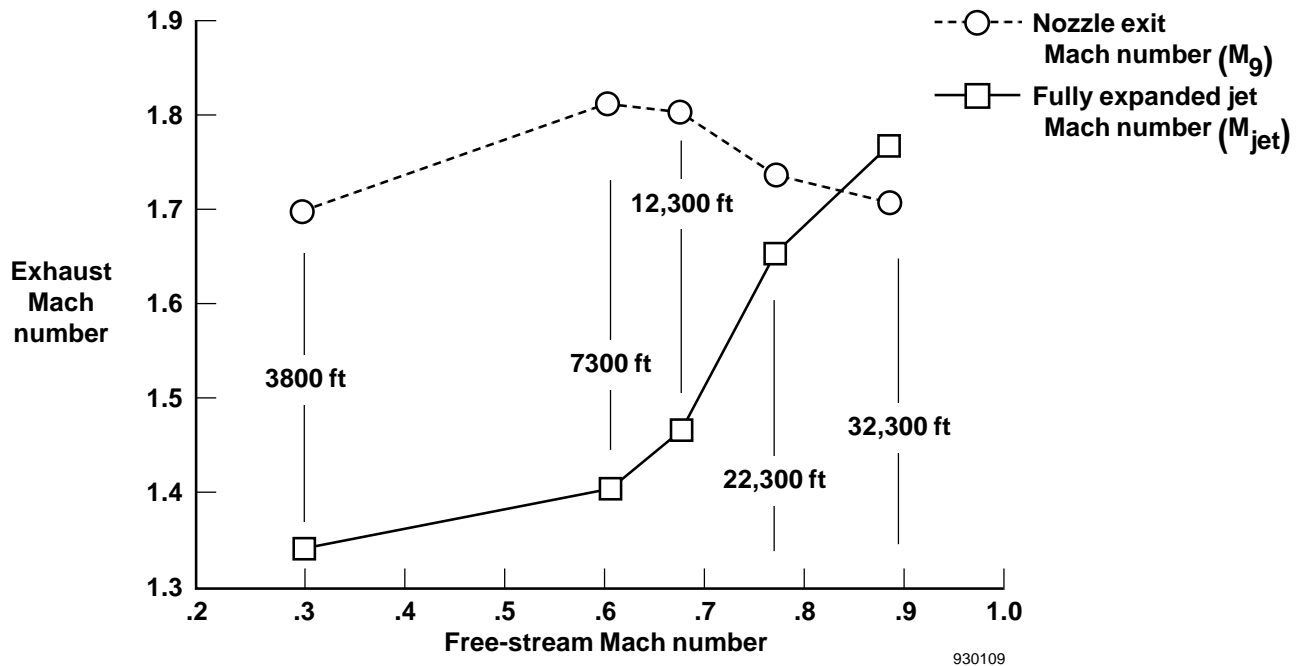


Fig. 3 Noise sources for an engine operating at high NPRs.

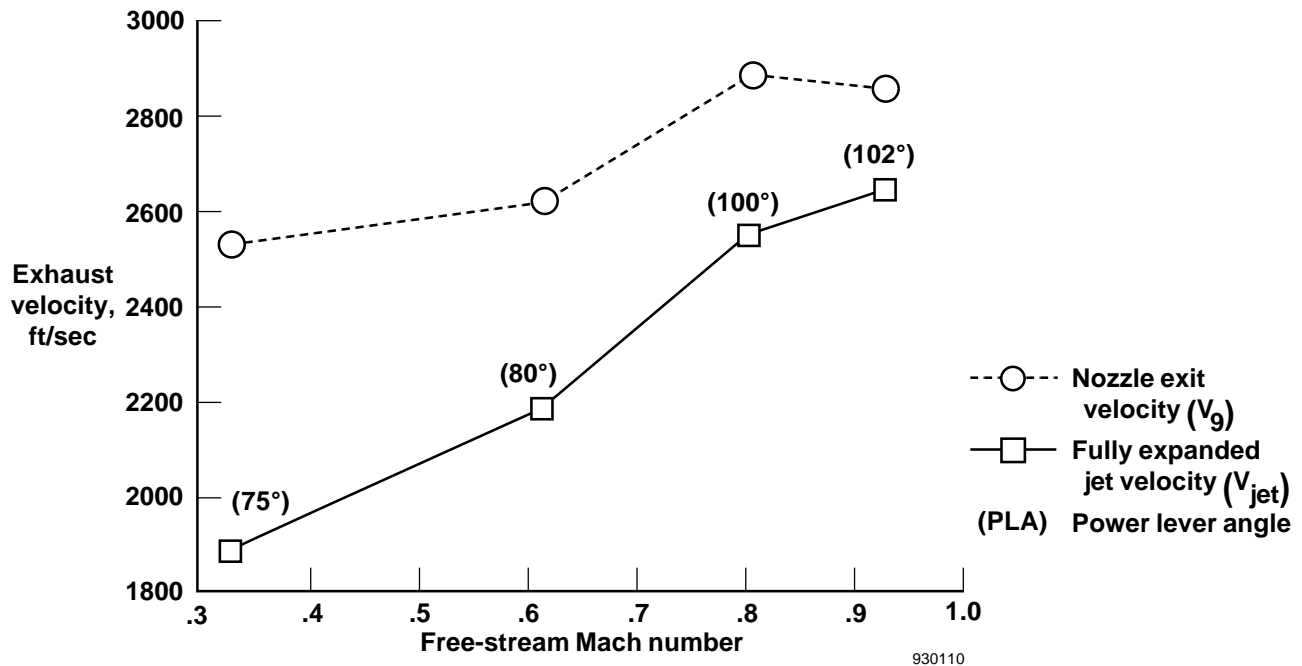


(a) Nozzle exit and fully expanded jet velocity.

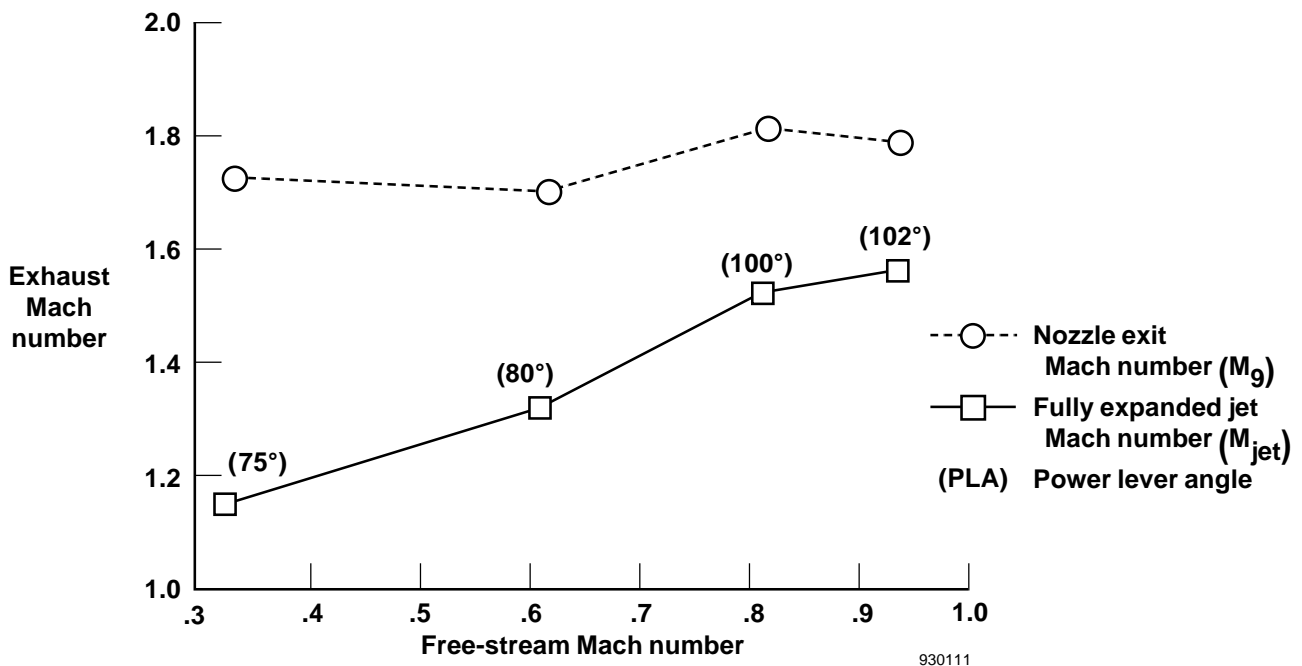


(b) Nozzle exit and fully expanded jet Mach number.

Fig. 4 Effect of Mach number and altitude on exhaust characteristics for climb-to-cruise test points, PLA setting at intermediate.

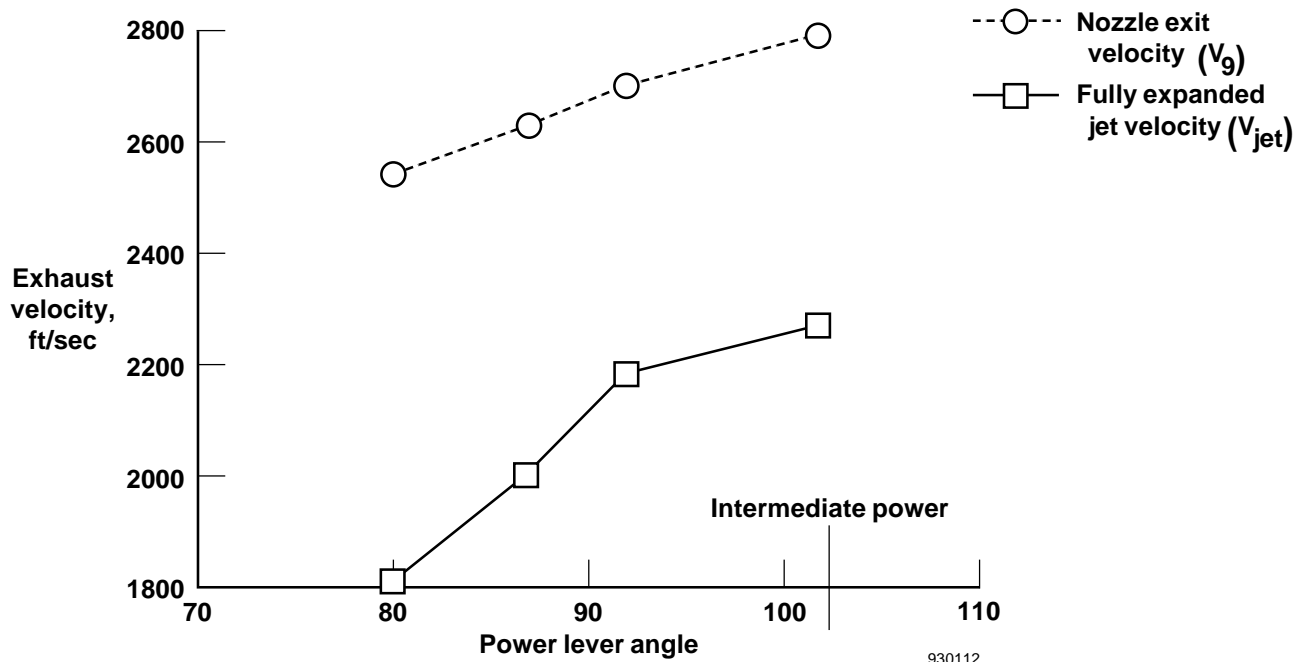


(a) Nozzle exit and fully expanded jet velocity.

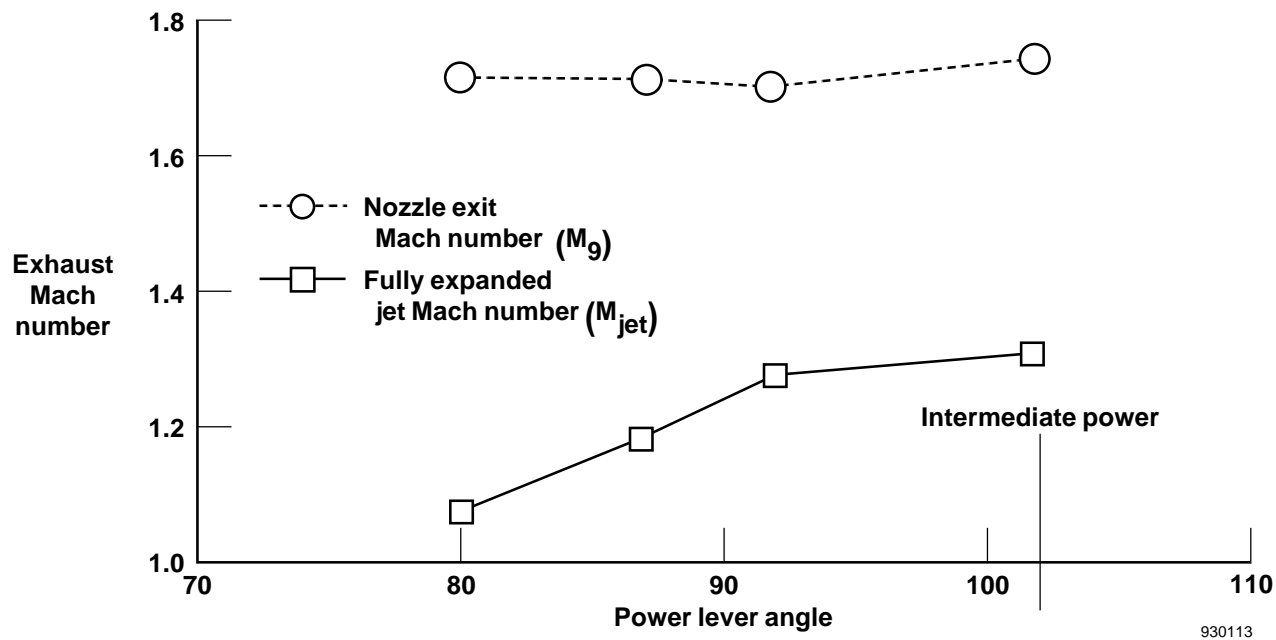


(b) Nozzle exit and fully expanded jet Mach number.

Fig. 5 Effect of Mach number on F404 engine exhaust characteristics for ANOPP test points, PLA setting at power for level flight (as noted).



(a) Nozzle exit and fully expanded jet velocity.



(b) Nozzle exit and fully expanded jet Mach number.

Fig. 6 Effect of PLA on F404 engine exhaust characteristics for ground static test points, 2300-ft altitude.

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13. ABSTRACT (Maximum 200 words) <p>Personnel at the NASA Langley Research Center (NASA-Langley) and the NASA Dryden Flight Research Facility (NASA-Dryden) have recently completed a joint acoustic flight test program. Several types of aircraft with high nozzle pressure ratio engines were flown to satisfy a twofold objective. First, assessments were made of subsonic climb-to-cruise noise from flights conducted at varying altitudes in a Mach 0.30 to 0.90 range. Second, using data from flights conducted at constant altitude in a Mach 0.30 to 0.95 range, engineers obtained a high-quality noise database. This database was desired to validate the Aircraft Noise Prediction Program and other system noise prediction codes. NASA-Dryden personnel analyzed the engine data from several aircraft that were flown in the test program to determine the exhaust characteristics. The analysis of the exhaust characteristics from the F-18 aircraft will be reported in this paper. This paper presents an overview of the flight test planning, instrumentation, test procedures, data analysis, engine modeling codes, and results.</p>				
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